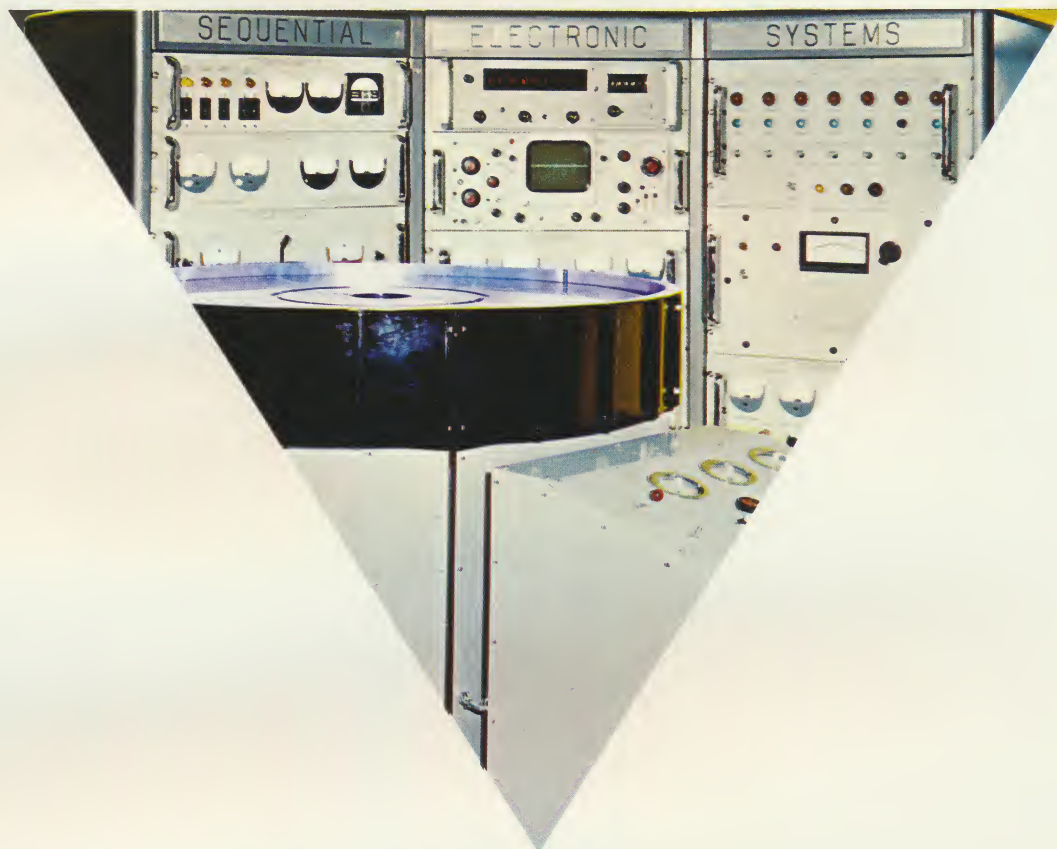




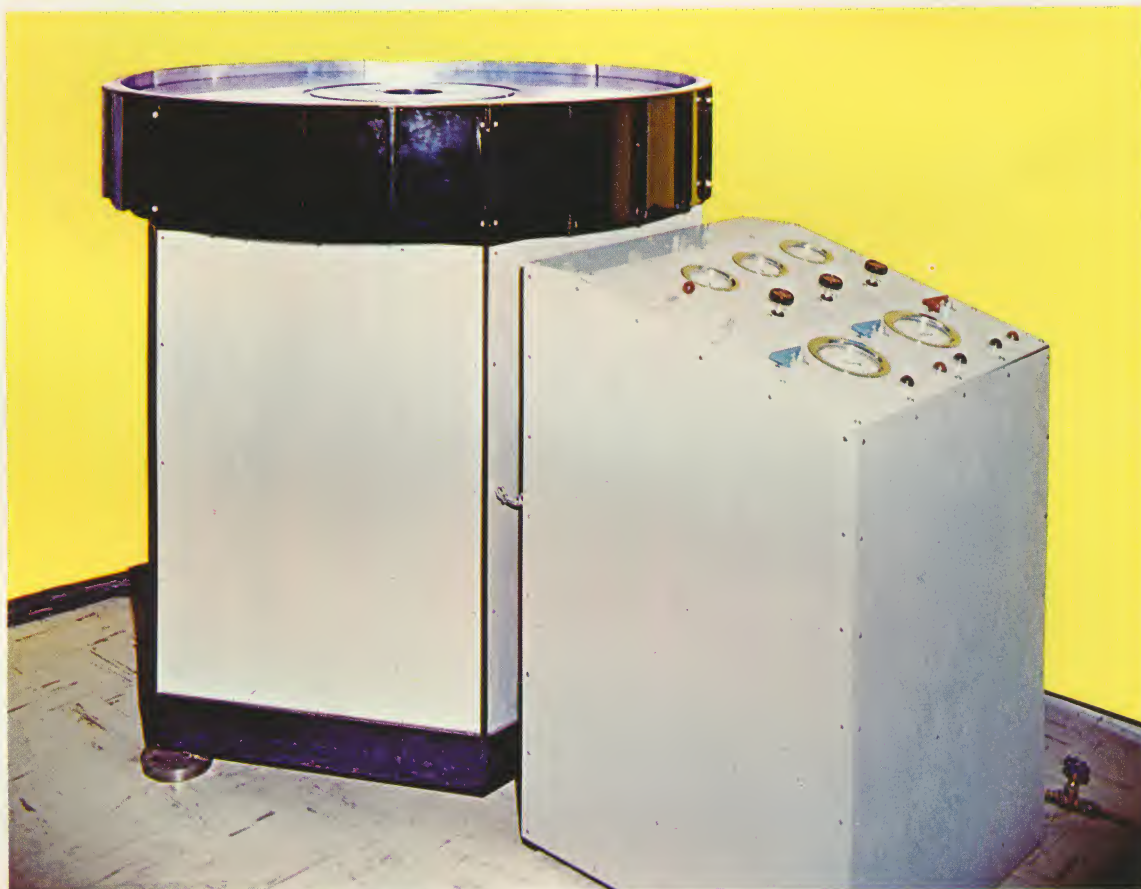
ULTRA
PRECISION
AIR BEARING
CENTRIFUGE

SEQUENTIAL ELECTRONIC SYSTEMS, INC.



Sequential ultra-precision air bearing centrifuge

Model ABC-7



INTRODUCTION

Sequential's Ultra-Precision Air Bearing Centrifuge Model ABC-7 is a major advance in the state-of-the-art for accelerometer testing. This equipment was designed specifically to meet industry's needs in testing accurate and extended range devices.

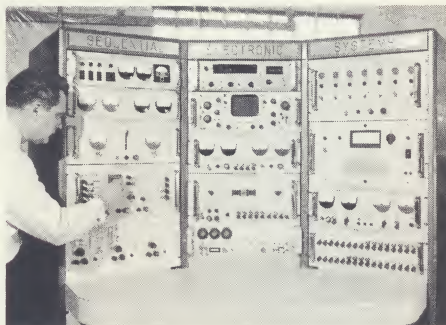
The Sequential air bearing centrifuge supplies accelerations of 0.01 to 150g's to the test specimen by operating over a speed range of 3.86 to 472 rpm (either direction of rotation). Earth rate operation can be supplied by using the Sequential Band-Scan FPL System* to control the table. Two enclosed wells, with an array of mounting holes are provided to allow the testing of two 6¼ x 6½ x 12 inches maximum size specimens at a mean radius of 24.5 inches. Additional wells are provided near and on the spin axis for mounting auxiliary equipment or a test specimen. The rotating centrifuge top is built in the form of a continuous circular table to minimize air drag and turbulence.

The specimen chamber is temperature controlled and allows for the testing of breadboard

and developmental instruments which often are not temperature compensated. The instruments under test are protected to the greatest extent possible against damage due to centrifuge failure. Should wheel speed result in excessive accelerations or the table unbalance becomes excessive, automatic controls gradually bring the table to a virtual stop before applying mechanical brakes. If the air bearing supply fails, a reserve supply keeps the table suspended until it is braked to a stop.

In addition, a mechanical switch cuts off the drive power when the table speed is equivalent to 175g's at the rim. This prevents catastrophic failures due to failure of a component in the servo loop or an accidental setting of the reference frequency to an incorrect value.

The centrifuge provides accurate, stable accelerations; the wow component of the wheel speed is equivalent to an acceleration of less than 150 micro g's at the maximum wheel speed. For an analog accelerometer, a potentiometric pickoff is available with the most noise-free slip rings and with the capability of handling two accelerometers simultaneously.



*Patent Pending

ACCURACY

The Model ABC-7 Centrifuge generates ultra-precise programmed accelerations for high accuracy testing of accelerometers. The Sequential FPL System operating in conjunction with a Sequential electro-optical encoder and Sequential air-bearing, controls speed of the centrifuge to better than 1×10^{-6} total instantaneous and long term inaccuracy. Accelerations are generated by mounting a test specimen on the centrifuge displaced from the center of rotation, with its acceleration axis exactly aligned radially so as to sense pure centrifugal accelerations.

Centrifugal accelerations will equal the product $r\Omega^2$; where r is the radius and is the rotational speed in radians/sec; at constant radius, programming of Ω will automatically set specimen accelerations. The total inaccuracy (assuming constant radius) in generation of specimen accelerations will be exactly twice the total inaccuracy of generating Ω . Variations in radius due to temperature or dynamic effects are monitored to better than 1 ppm; therefore, total absolute inaccuracy of acceleration is held to less than 3 ppm.

The speed accuracy of the centrifuge is constantly monitored by measuring time between known index marks on the encoder disc. As indicated in the monitoring equipment photograph, the time is measured using a 10 megacycle clock and a pre-set counter.

DESCRIPTION

CONTROL SYSTEM

The Sequential FPL System is a frequency-phase locking control system. The system reference is a precision free-running master clock of frequency f_r . In synchronism, the electrical pulse train, f_s , from the Sequential encoder, corresponding to coincidence of lines on the Sequential optical disc with reference lines on the optical reading station, is phase-locked to the reference frequency f_r . Frequency-locking assures that for out of synchronism conditions, full acceleration or deceleration is applied to the centrifuge in order to automatically attain synchronism. In addition, the FPL system assures that there is a smooth and continuous transition from the frequency-locking mode to the phase-locking mode to eliminate the possibility of limit-cycling due to control nonlinearities.

Bi-directional control is implemented so that full power can be utilized for both acceleration and deceleration conditions.

In synchronism, the steady-state torque applied to the bearing is directly proportional to the relative electrical phase between f_r and f_s . Transient applied control torques are directly proportional to relative electrical phase, and first and second derivatives. Relative proportionality constants are adjusted for "tight" system damping and most effective inertial characteristics. For out of synchronism conditions, air-bearing acceleration is not fed back into the con-

trol system to minimize the time required to attain synchronism.

The number of lines on the optical disc is such that the minimum sample rate, f_s , of the control system is on the order of 1KC ($f_s = \frac{\Omega N}{60}$).

Ω = rotational speed in rad/sec, N = number of lines on optical disc). This insures that for control effectiveness the digital monitoring of speed/position coordinates introduces no significant transport lags, and for all dynamic considerations thereby acts as a continuous system. The addition of the Sequential D/A Converter* insures that pure analog error signals are available in order to apply analog dynamic stabilization. This hybrid type of instrumentation produces an optimum controller that fulfills the necessary conditions of both high accuracy and superior dynamic performance. For a more complete discussion of the FPL System and Band-Scan FPL System see Sequential's Film Drive Systems data sheet.

MECHANICAL AND ELECTROMECHANICAL

The centrifuge consists of a 24.5-inch circular table mounted on a hydrostatic gas film bearing. The bearing will consume approximately 5SCFM of air at a supply pressure of 60 psig. In the event of gas supply failure, a reserve supply is activated and the table is dynamically driven to a safe halt. The gas bearing is stiff enough so that at the maximum loading of 150g's, the maximum spindle axis wobble is less than 25×10^{-6} inches. Wobble and runout can be continuously monitored with a precision of better than ± 1 micro-inch. The table is totally enclosed in a sealed chamber to improve stability and permit temperature control. The temperature of the test fixture may be controlled to 0.2 deg C. A thermal sensor placed directly on the test specimen reads accelerometer temperature to within 0.02 deg. C. The purpose of this control is twofold: (1) the variation of accelerometer nonlinearities and scale factor with temperature is easily measured, (2) it is possible to test developmental and breadboard instruments which may require a closely controlled thermal environment. The table is driven by a reversible DC torque motor. Typical of the conservative design involved is the fact that at maximum rated speed, the motor draws less than 50 percent of rated operating current.

Auxiliary equipment required for continuous monitoring of performance characteristics is mounted adjacent to the air-bearing and on the table. This equipment provides radius stability "coning" measurement to derive the quality of dynamic balancing and auxiliary fine compensation adjustment, and accelerometer derived checkout of short term velocity perturbations.

The centrifuge is 5½ feet in height and completely enclosed in a practical housing. Top and side hatches provide access to the specimen, slip rings, and other instrumentation. The interior of the tub is aerodynamically clean. A glass window and an interior light are provided. The air temperature within the

tub is controllable over a 100° to 160°F range within $\pm 5^\circ\text{F}$.

The control system, power supplies, additional checkout equipment, and remote programmers are contained in a remote AMCO cabinet.

DROOP, RADIUS, AND TABLE WOBBLE

The centrifuge table is so designed that the droop or angular change of position of the table is small enough (less than 5×10^{-7} radians) at maximum load so as to be completely negligible. The radial growth of the centrifuge table is measured to an accuracy of 1 ppm of the table radius by a capacitance probe. A piece of metallic tape and a micrometer form the electrodes of the capacitor which is part of a resonant circuit. The micrometer adjustment is used to calibrate the output response of the resonant circuit and is set for best linearity. The magnitude of the resonant circuit response is then used to read the radial growth when the machine is in operation.

SPECIMEN HANDLING WELL

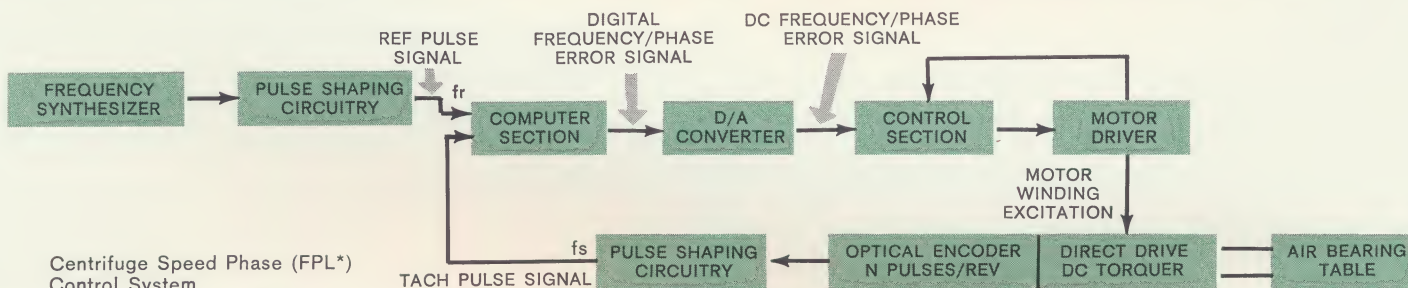
The centrifuge is designed to handle specimen loads of up to 50 pounds with a maximum size of $6\frac{1}{4} \times 6\frac{1}{2} \times 12$ inches. Two such units may be tested simultaneously by mounting the units in two test fixtures 180 degrees apart on the centrifuge wheel. Equivalently, two units may be tested in the same fixture simultaneously if the size and weight specification can be met. The specimen can be aligned within 0.5 arc-second to the vertical. The mounting fixture can be inverted to allow the application of positive and negative accelerations.

SLIP RINGS

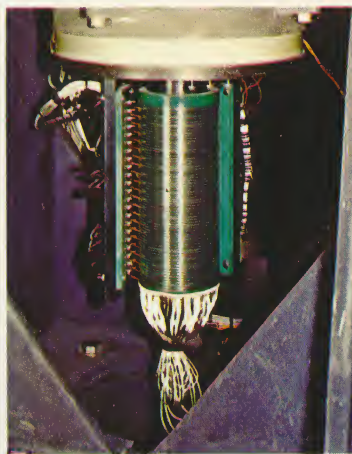
Electrical connection to the table is made by means of 44 slip rings. If necessary, space is available for additional slip rings up to a total of 66. Three brush blocks are used to facilitate in-field repair. Only two blocks are operational. One block is for the 22 spare slip rings. The slip rings are of three types, consisting of 20 signal rings, 20 power rings, and 4 thermocouple rings. The signal rings are rated at 1 ampere continuous current and produce a maximum of $5 \mu\text{V/MA}$ of noise at all table speeds. Cross talk between rings is down 25 db at 25 kc into a 50 ohm load. The power rings are rated at 5 amperes continuous load, and can tolerate a 25 ampere load for one-half second before the fuse protecting the ring open-circuits. The thermocouple rings are specially designed to match the thermocouple circuits which monitor the accelerometer temperature.

PNEUMATIC CONTROL CONSOLE

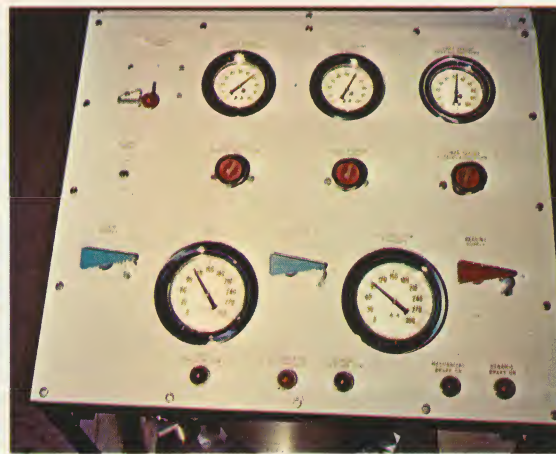
This console contains all the controls to set the radial and thrust bearing pressures. A ten minute accumulator is also included in the event of failure in the main air supply. Automatic interlocks will dynamically brake the system to a stop in less than 3 minutes. These built-in safety features provide additional protection for the air bearing.



Specimen Handling Well



Slip Rings



Pneumatic Control Panel



Monitoring Equipment

OPTICAL ENCODER

One of the most important building blocks of the centrifuge control system is the optical encoder. The encoder disc is integrally mounted to the centrifuge bearing structure. The coded disc has a data track which produces 23,040 pulses per revolution and an index track which produces one pulse per revolution.

cell does not occur. Due to diffraction, scattering, and dispersion-effects, the photocell actually sees an average light intensity at all times with a signal component proportional to centrifuge rotational speed. The ratio of signal to average d.c. light is directly a function of the track density, and the amplitude of the d.c. component

Model ABC-7 electronic control console



The data track has 23,040 opaque and 23,040 alternate clear segments. The master disc was manufactured by Sequential on its unique electrically programmed Automatic Circle Dividing Machine. Line positions on the data track have a calibrated accuracy of 0.33 arc-seconds.

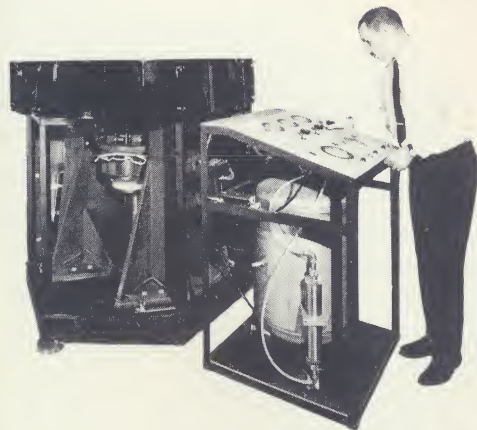
An optical readout system is used to read the disc. A collimated light from the lamp excitation assembly is transmitted to the data track and focused through the track onto a reticle grating containing a line pattern with the same density as the data track. A photocell, mounted on the opposite side of the grating senses the light as it passes through the grating. As the centrifuge rotates, the light pattern produced by the disc moves across the grating, and the grating pattern alternately blocks and passes light to the photocell. The photocell output is amplified by a readout amplifier. The output from the readout amplifier is a sinusoidal signal that repeats 23,040 times per revolution. This output signal is passed to pulse shaping circuitry that produces a sharp pulse at each positive-going, zero cross-over of the sinusoidal signal.

In actuality, a complete blocking of light to the photo-

cell can be several times that of the signal. In order to remove this d.c. component and preserve the signal, a differential readout technique is used. Two channels are provided and phased so that when their photocell output are added differentially, the d.c. components cancel and their signals add.

These two channels are implemented with a locked beam technique which provides an identical optical path from the lamp to each photocell pickoff. Since the optical paths are the same for each station in a differential pair, relative bulb movements, due to variations in filament "hot-spot", or light intensity loss due to bulb aging, will not have significant effect on the zero level or relative phasing of a readout station, and will manifest itself only in changes in signal amplitude which does not significantly affect encoder accuracy.

In order to cancel all significant harmonic errors, multiple readout stations are used for readout of the data track. The significant harmonic errors are first harmonic due to disc centering, and second harmonic due to disc elongation caused by the large center hole. These errors are reduced to a level below 1.0 arc-second.



SEQUENTIAL ELECTRONIC SYSTEMS, INC.



SEQUENTIAL

ULTRA-PRECISION AIR BEARING CENTRIFUGE

FEATURES

- One hundred times more accurate than existing equipment
- Better than 1 PPM velocity accuracy
- Better than 3 PPM acceleration accuracy
- 0.01 to 150 g's acceleration range
- Droop uncertainty ± 0.1 arc-sec
- Dynamic balancing controllable from console
- Fail-safe automatic safety interlocks
- Pushbutton control — elaborate start up procedure eliminated

SPECIFICATIONS

Radius	24.5 inches
Acceleration Range (nominal)	0.01-150g's
Speed Range (nominal)	3.86 to 473 rpm
Specimen Size	A — 6 $\frac{1}{4}$ " x 6 $\frac{1}{2}$ " x 12" (two areas available) B — auxiliary mounting area
Specimen Weight	50 lbs.
Relative Acceleration Accuracy	better than 3 ppm
Short Term Speed Stability	better than 1.0 ppm
Long Term Speed Stability	better than 0.5 ppm
Resolution of Dynamic Radius Comparator	± 0.5 ppm
Spindle Verticality Adjustment Resolution	better than 0.5 arc-secs
Balancing	Controlled from console while in motion
Table Droop Uncertainty	± 0.1 arc-sec
Speed Change (Minutes)	4 $\frac{1}{2}$ minutes to 150 g's
Stopping Time	3 minutes max. by dynamic braking
Rotation Direction	cw or ccw
Motor	10 ft lb dc torquer
Slip Ring System	66 Slip Rings; 6 thermocouple, 30 power (5 amp capacity), 15 low noise signal and, 15 signal (1 amp capacity)



SEQUENTIAL ELECTRONIC SYSTEMS, INC.

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SYNCHRO AND SYNCHRO-TO-DIGITAL CONVERTERS • SPECIAL PURPOSE DIGITAL COMPUTERS



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